

The University of Chicago

THE DISTRIBUTION  
OF ELECTRICITY ON ROTATING  
METALLIC CONDUCTORS

A DISSERTATION SUBMITTED TO THE FACULTY  
OF THE DIVISION OF THE PHYSICAL SCIENCES  
IN CANDIDACY FOR THE DEGREE OF DOCTOR  
OF PHILOSOPHY

DEPARTMENT OF CHEMISTRY  
JUNE, 1942

By  
MELVIN S. FREEDMAN

CHICAGO, ILLINOIS

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I wish to express my thanks to Dr. Simon Freed for encouragement and assistance during these experiments. I also wish to thank Dr. S. I. Weissman for his aid and advice in the designing of the apparatus.



Since Faraday's attempts to demonstrate an interaction between dynamical and electrical forces, the course of such investigations has made apparent two major experimental difficulties. First, it was early evident that only extremely small changes in the state of electrification of a conductor could be produced solely by rotational stresses. Second, the available measuring techniques introduced relatively large spurious deviations which masked the effects under consideration.

Notwithstanding these limitations, many investigators<sup>1</sup> achieved sufficient indications of a positive correlation to make further efforts worth while. The recent development of simpler means for obtaining very high speed rotation with air driven turbines make it possible to stress metals radially even to the yield point. Further, the vibrating electrode technique for measurement of contact potentials seemed a means whereby electrostatic induction could supplant direct physical contact to the rotating conductor, and thus eliminate thermo-electric and electrostatic effects at brush contacts. The work of S. I. Weissman<sup>2</sup> proved that such measurements on a completely "isolated" conductor are impossible, since under no attainable conditions could the static charge upon such a "floating" object be kept constant. However, by use of a needlepoint contact to a liquid conductor and a vibrating electrode adjacent to the periphery of a spinning rotor he succeeded in obtaining measurements significant, over short periods, to  $10^{-5}$  volts.

Let us consider such a system composed of a rotating disc,

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<sup>1</sup>"Maxwell's Treatise on Electricity and Magnetism," Clarendon Press, London, 1892, 3d ed., II, 211.  
Hertz, Wiedemann's Annalen der Physik und Chemie, 14, 581-90 (1881).

Nichols, Physik Z., 7, 640 (1906).  
R. C. Tolman and Dale Stewart, Phys. Rev., 8, 97 (1916),  
9, 164 (1917); Tolman, Heurer and Geurnsey, 21, 525 (1923);  
Tolman and Mott-Smith, 28, 794 (1926).

<sup>2</sup>S. I. Weissman, "Some Electrical Phenomena in Rotating Metallic Conductors" (Unpublished Ph.D. dissertation, Department of Chemistry, University of Chicago, 1938), p. 13.



a conducting connection to a potentiometer, a resistance and a metallic electrode adjacent to the periphery of, and made to vibrate along a radius of the rotor (Fig. 2). It can be shown<sup>1</sup> that if and only if the sum of the contact potential between the rotor periphery and the electrode, plus the potential across the terminals of the potentiometer, plus the E.M.F. due to rotation is equal to zero, then no alternating currents flow through the resistor  $R_1$ , and conversely.<sup>2</sup> This furnishes a convenient method for measuring the E.M.F. due to rotation. One observes the minimum in the output of a detector of the alternating current flowing in the resistor  $R_1$  as the potentiometer voltage is varied. If the assumption is made that the contact potential existing between two metals is independent of the rotation of one of them,<sup>3</sup> then the variation in the potentiometer setting with change in rotational velocity is a measure of the difference in the E.M.F. generated at the two speeds, since what one actually measures is the contact potential plus the E.M.F.

It will be noted that it was not possible to reduce the output of the detector amplifier completely to zero. The minimal response is due to voltage variations inherent to the amplifier and to the resistors  $R_1$  (thermal agitation noise, shot effect, etc.), and to an alternating voltage of frequency equal to the rotational angular frequency which the electrode picks up electrostatically from the rotating system (later to be referred to as the "rotational wave"). That this latter component may be due in part to a "generator" effect is indicated by the results of S. I. Weissman,<sup>4</sup> wherein it appears that the spinning rotor is accompanied by a rotating electric field whose angular distribution does not correspond to that of the contact potential around

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<sup>1</sup>Ibid., p. 5.

<sup>2</sup>Subject to the limitations that the charge on the system remain constant (insured by a conductive connection to the rotor and a common grounding point); that the external magnetic and electric fields remain constant; that the system be isothermal and at rest with respect to the observer.

<sup>3</sup>The distinction between a contact-potential which varies with rotation and an E.M.F. due to rotation cannot be made by such an electrostatic measurement.

<sup>4</sup>Ibid., p. 15.

the periphery of the stationary rotor. There are eddy currents induced in the spinning conductor by the component of the surrounding magnetic field in the plane normal to the axis of rotation. If the conductivity of the rotor material is not a function of the radius only, the I R drops due to these eddy currents may alter the equipotential character of the surface of the rotor so that, to the observer outside, a rotating electric field is carried along with the rotor.

There remain to be analyzed several possible sources of an E.M.F. due to rotation, besides that due to dynamical effects in the body of the rotor. It was assumed for this experiment that the spinning needle point contact to the liquid metal does not generate a potential difference in the circuit different from the normal contact potential between these metals. The phenomenon of unipolar induction will, in the presence of an axial component of the external magnetic field, produce a radial potential difference superimposed upon that under consideration. This effect was minimized by elimination of ferromagnetic material in the construction of the apparatus, and its magnitude may be calculated by performing the experiment for equal speeds in opposite senses of rotation. The unipolar induction potential will alter signs with change in the direction of rotation, whereas the sign of the "dynamical" E.M.F. should be independent of this change.

We may attempt an estimation of the magnitude of the effect based upon the simplest considerations, i.e., that the centrifugal forces on the electron swarm in the metal are equilibrated by an electric field, so that:

$$E e = m \omega^2 r$$

where  $E$  is the electric field,  $e$  is the charge and  $m$  the mass of the electron,  $\omega$  the angular velocity and  $r$  the radius of the rotor. Thus with a rotor of four inch diameter at a speed of two thousand revolutions per second the generated E.M.F. is just one microvolt. In this model no account is taken of possible effects which might be characteristic of the chemical nature or crystal structure of particular metal under investigation. Thermal diffusion of the electrons will certainly play a part in determining the equilibrium distribution of charge. There may be important variations of secondary character from the interaction of the magnetic fields due to the rotating charges upon the charges them-



selves. These and other factors so complicate the simple dynamical picture that even the predicted order of magnitude may well be in great error. Since even minor stresses critically effect contact potentials, it seems likely that the tremendous stresses accompanying such rotational velocities as would almost rupture the rotor (about 3300 R.P.S.) would cause effects far too large to be calculable on so naive a basis.



## EXPERIMENTAL

A description of the course of these experiments is best achieved by a survey of the apparatus in its present form. The problem began as a continuation of the work of S. I. Weissman<sup>1</sup> on the apparatus which he had developed. Early in the work a large but erratic leak appeared in the system which several months of struggle could not permanently eliminate. Since the construction of the apparatus presents several serious limitations to modifications under consideration, it was decided to construct a new mechanism (Fig. 1).

It proved desirable to modify the rotating mechanism so that measurements could be made on the rotor spinning in the clockwise and in the counterclockwise directions within a moderately short time. Further, difficulties in stopping the rotating system from high speeds without an independent air supporting bearing and air driving pressure led to the adoption of a system modified from that used by Beams and others.<sup>2</sup> The flat driving rotor (#16, Fig. 1) independently supported and driven, was made with two sets of flutings in opposite senses, one being used for driving and the other for braking, and vice versa.

The supporting air bearing consisted of a highly polished clear bakelite ring (#14, Fig. 1) flexibly mounted on a neoprene toroid (#15, Fig. 1), which was loosely fastened above the supporting-air chamber (#26, Fig. 1). This chamber, manually centered with respect to the main bearing (#10, Fig. 1) and locked, was carried on a movable framework (#39, Fig. 1) fastened to the cover of the vacuum chamber (#38, Fig. 1). The driving jets (#22, Fig. 1) and pressure-equalizing chambers were locked to the supporting-air chamber by a threaded ring. Above the driving jets was mounted the floating upper bearing (#27, Fig. 1).

A series of unfortunate and very destructive accidents with the older apparatus in which the flexible shaft broke while

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<sup>1</sup>Op. cit.

<sup>2</sup>Beams, Linke and Sommer, Rev. Sci. Inst., 9, 248 (1938)

spinning at high speeds, seemed best remedied by replacement with a heavier shaft. A  $3/32$ " hardened beryllium copper shaft (#11, Fig. 1) plated with a .0005" thick layer of hard chromium (for wear resistance) proved an excellent choice. According to the results of S. I. Weissman,<sup>1</sup> ferromagnetic materials, even the so-called "nonmagnetic stainless steels," could not be used, due to their residual magnetism. The use of such heavy shafts necessitated extreme straightness. A great deal of time was spent on this simple problem without finding any consistently satisfactory solution.

Special reaming tools were used in the bearing manufacture to avoid the use of any lapping compound, which proved difficult to remove from the bearing surfaces. It was possible to obtain such excellent bearing clearances (about .00005") that the oil consumption at a speed of 1500 R.P.S. was reduced to about one-third cc. per hour.

A familiar problem in the operation of such ultracentrifuges, the formation of standing waves along "free" loaded sections of the shaft was most successfully eliminated by minimization of the unsupported length. It may be worth noting that in the several years combined experience of S. I. Weissman and the author, it was never possible to attain satisfactorily smooth rotation if the free shaft between main bearing and large rotor (#1, Fig. 1) was longer than 2 mm. Efforts to shorten the unsupported shaft length above the main bearing led to the adoption of a long upper section of the bearing, which proved a fortunate choice. Previous to its use we had had the experience common with ultracentrifuges of severe vertical vibration on the supporting air column, which could only be eliminated by precise and difficult adjustment of the air pressure. With the bearing inserted into the supporting air chamber, and an opening left to the atmosphere below, the aerodynamics of the system were modified so that the following results obtained. Below a certain critical pressure the rotating system was stably supported in each of two positions separated vertically by a small fraction of a millimeter, the lower one still subject to vibrations, the upper one completely free of them. At any pressure above this critical

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<sup>1</sup>Op. cit., p. 15.



value (60 lbs.) the lower position became metastable with respect to the upper and all corresponding oscillations were removed.

To dampen vibrations of the shaft above the small driving rotor several types of bearings were tried; that finally adopted was a floating bearing free to move in the horizontal plane and surrounded by a heavy grease to absorb its vibrational energy. This portion of the entire apparatus was the most sensitive indicator of vibration anywhere in the rotating system, yet for the smoothest spinings no evidence of motion was discernible here. Light machine oil was supplied to the bearing under five pounds air pressure.

The main rotor itself, about four inches diameter, was turned from a forging of duralumin 14 S.T. and was x-rayed for flaws. Its upper portion (#2, Fig. 1) was formed cup shaped to function as part of the mechanism designed to prevent the oil which passed through the main bearing from reaching the outer clean surface where measurements were made. Seal was made to the main body with a pure gum rubber gasket. To prevent spurious electrical input resulting from the frictional forces between the shaft and bearings it was necessary to insulate the main body of the rotor from the rest of the rotating system, and to maintain low capacity by means of large clearances between these portions. This was accomplished by the use of a large piece of clear bakelite (#3, Fig. 1) in which the chuck (#19, Fig. 1) and shaft were mounted. The necessary exact centering of these parts is difficult to maintain, for the bakelite undergoes slow plastic deformation which has to be continually corrected; unfortunately no better material could be found.

At the bottom of the rotor was mounted a beryllium copper screw (#4, Fig. 1) machined to a needle point. To this point electrical contact was established while rotating, by means of a small pool of liquid metal (#5, Fig. 1), a 20% solution of indium in gallium, the eutectic, which melts at about 5°C. Pure gallium, which melts above room temperature, occasionally gave trouble by suddenly crystallizing. The use of mercury is prohibited by its vapor pressure of  $10^{-3}$  mm. Hg. at ordinary temperatures, while gallium, which boils at about 2000°C., has at room temperature a vapor tension negligible for this experiment. To assure a reliable contact it was necessary to maintain a clean shiny surface on the gallium. Extended purification and frequent scraping of

the surface film was usually sufficient. The position of the pool could be controlled from outside the vacuum chamber, so that contact to the rotor could be established after smooth rotation was achieved. The device for raising and lowering the pool involved the use of a long finely threaded screw (#46, Fig. 1) and nut (#47, Fig. 1) packed with a vacuum grease made of Apiezon wax and Molecular Lubricant C. This seldom showed any trace of vacuum leak, even when turned.

The system supplying oil to the main bearing consisted of two steel pistons and cylinders lapped to a close fit, and suitable packless, sylphon type valves. One piston, spring actuated, delivered the lubricant to the gland through an "isolated" lead at 15 lbs. pressure, while the other served as an oil reservoir. The oil used, Molecular Lubricant C, has a vapor pressure guaranteed by the manufacturer to be less than  $10^{-6}$  mm. Hg., but even short exposure to air results in relatively large absorption of air and water vapor. To remove these substances and any other volatile constituents, the space above the oil in the reservoir was evacuated to invisible discharge by a small three stage mercury diffusion pump backed with a Cenco Hyvac. Violent foaming of the cold oil was avoided by an electrical heating coil surrounding the reservoir trap. The purified oil could then be forced into the pressure cylinder anaerobically, and thence to the bearing. With oil in the bearing in contact with the evacuated chamber, the ionization gauge frequently registered as low as  $10^{-7}$  mm.

As will appear later, the most scrupulous care must be taken to maintain the measuring surfaces "clean." A drop of oil reaching the exposed surface of rotor or electrode is fatal to the measurement, and so several precautionary measures were used to prevent this. During a "run," pumping over long periods of time, i.e., up to several days, with the rotor stationary, was necessary, and then oil sealing the vacuum in the main bearing would slowly seep down along the shaft and onto the rotor. A limited amount of this could be collected in the rotor cavity, but an excessive amount was intolerable. A successful technique which restricted the oil leak to a few drops per day consisted in raising the rotor from the upper end of the shaft until the rotor chuck contacted a small Koroseal ring integral with the bearing; when spinning, the rotor was lowered. Oil forced through the bearing during rotation was centrifuged from the shaft by a small



disc and collected in a chamber (#8, Fig. 1).

It was evident from the start of the experiment that the phenomena under investigation undergo simplification in very high vacua, and all elements of the design followed this consideration. The vacuum chamber (#37, Fig. 1) itself was made from 8" rolled brass tubing with all joints silver soldered, the whole then dipped several times in molten tin, and then all joints covered with pure tin solder. Join was made to the glass vacuum line with a flexible 2" diameter metal hose and a "well" joint sealed with Apiezon wax. The cover of the vacuum chamber, on which the rotating system was mounted, bore a flange (#35, Fig. 1) on its rim which dipped into an annular well (#33, Fig. 1) on the upper edge of the chamber wall. The vacuum was sealed by a layer of Apiezon wax (#34, Fig. 1) in this well, which was melted by means of a ring Bunsen burner (#36, Fig. 1) beneath; then the cover was lowered into contact with its aligning surface and the molten wax. After the wax was cooled by water circulating in several turns of copper tubing soldered to the chamber wall, an almost invariably perfect seal resulted.

The remarkably fast vacuum system, consisting of two mercury diffusion pumps in series, with large cold traps, easily attained pressures of  $10^{-6}$  mm. Hg.

Two electrical leads, one to the vibrating electrode (#6, Fig. 1) and the other to the gallium pool, were introduced through the chamber wall by using large bakelite insulators threaded into the side of the vacuum pot, carrying a small conducting screw concentrically, and the whole made vacuum tight with Apiezon wax. The resistance-to-ground of the insulated conductor never tested less than  $10^{13}$  ohms. Also soldered to the vacuum chamber wall was the bearing (#30, Fig. 1) through which the shaft supporting the vibrating electrode was introduced. A six volt headlight lamp with the base removed, and supplied through bakelite insulators similar to the above, furnished the illumination for observation of the rotor and electrode. Three 1/2 glass discs (#40, Fig. 1) sealed into the cover with wax served as windows.

In an effort to minimize the unipolar induction phenomena resulting from stray axial magnetic fields no ferromagnetic materials were used in the construction of either the apparatus or the surrounding barricades. It was hoped that the protection

afforded by a heavy framework of 6" seasoned oak held together with large duralumin bolts plus a 4" brass-reinforced concrete wall would be sufficient in case of explosion. This was one portion of the apparatus whose efficiency we were very happy never to have tested.

A most vexing problem was that of obtaining a sufficiently powerful mechanical oscillator with which to drive the vibrating electrode. The necessary compromise between the available mechanical power and the frictional load losses in the bearing transmitting the vibration, forced the continued use of a small (.040") and extremely flexible shaft (#7, Fig. 1). On the inner end of this shaft, and insulated from it by a shielded screw and washer of clear bakelite (#28, Fig. 1), was mounted the electrode. This was cut from a piece of duralumin 14 S.T. of the same forging from which the rotor was turned. It was shaped into a circular arc of approximately  $90^\circ$  length and of a radius of curvature matching that of the rotor. Electrical connection was established through a short piece of 2 mil copper wire soldered to one of the beryllium copper pins holding the electrode to its mounting. At the outer end the electrode shaft was soldered to the arm on a corner of the piezo-electric crystal which was the source of mechanical power. Vacuum seal was made in the bearing by forced supply of heavy Apiezon K oil. The oil seeping through the bearing into the vacuum chamber was collected from the shaft by a small glass-thread filter and thence into a receiving cup.

For the highest measuring sensitivity, the solution of the differential equations describing the vibrating electrode require that the mean capacity between rotor and electrode be as high as possible. It was therefore imperative to achieve and maintain very good alignment of the electrode with respect to the rotor, such that the mean distance between their surfaces could be reduced to about one-tenth millimeter. The extremely slender beryllium copper electrode shaft made this difficult. Several devices such as variable tension springs and guides gave little improvement, for one could not depend on the shaft remaining straight while one handled it in machining the electrode. We finally successfully completed the alignment by shifting the cover of the vacuum chamber carrying the entire rotating system in a horizontal plane by means of variable clamping screws, observing simultaneously the clearance between rotor and electrode from outside with



a long focus, ten power microscope.

It was also necessary to correct the electrode alignment for rotation around the electrode shaft as axis, since the electrode had to be aligned by hand while the shaft was being soldered to the crystal arm. Therefore we mounted the entire piezo-crystal on a frame work which could be turned around this axis, and this whole in turn was mounted upon a calibrated brass slide for moving the electrode radially towards the rotor. The crystal was driven by a heterodyne audio-oscillator and a power amplifier. Frequency drifts in the oscillator made it very difficult to remain tuned to the sharp response peak of the detecting amplifier. Dr. Warren Henry kindly loaned us a tuned grid oscillator which, with slight modification, was very stable, i.e., extreme variations of one cycle per hour. Means were provided for maintaining the temperature of the Rochelle salt crystal below  $24^{\circ}$  C., above which temperature its piezo-electric response becomes almost nil.

A simple and very reliable stroboscope for observation of the rotational speed consisted of a beat frequency audio-oscillator driving a class C. power amplifier. The source of illumination used was a 4 watt neon bulb; with this a small black spot on the surface of the small rotor was readily visible at synchronization.

The electrical circuit used as detector of the alternating currents induced between the vibrating electrode and the peripheral surface of the rotor comprised a potentiometer, an extremely high gain, sharply tuned audio-amplifier (Fig. 2), and either an oscilloscope or a rectifier and microammeter as output indicator. During these experiments we had available both a Leeds and Northrup Type K2 and a White double thermocouple potentiometer of one microvolt sensitivity. Although occasionally the limited range (.01 volts) of the White was exceeded, and though the Type K2 possessed some slight advantage in speed of reading over large ranges, the extreme reproduceability and freedom from thermal and spurious contact noise voltages of the White potentiometer made it the greatly preferable instrument. In addition, its lower working current drain eliminated the need to correct for slow zero drifts during long runs.

From the experimental results of S. E. Weissman<sup>1</sup> it seemed likely that the effects we were seeking were so small as to re-

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<sup>1</sup>Op. cit.

quire a D.C. sensitivity in the range of ten microvolts or lower. Several spurious phenomena and certain properties inherent to the nature of the source of the current being detected had to be minimized in order to realize such sensitivities.

Due to mechanical difficulties it is not easy to achieve high vibrational amplitudes of the electrode at high frequencies. At the frequency chosen, 250 cycles per second, the reactance of the electrode-rotor capacity approximates  $10^8$  ohms. The impedance matching input resistor manifests, at room temperature, thermal agitation voltages of several hundreds of microvolts over the frequency spectrum passed by the amplifier. Also, as will appear later, when measurements were made during rotation, an alternating voltage of the rotational frequency with amplitude up to hundredths of a volt was induced in the input circuit. The detection of the relatively tiny signal superimposed on such a rapidly varying background proved possible, only by tuning the amplifier very selectively to the signal frequency, 250 c.p.s. This was done by employing an inverse feedback network including a modified Wien bridge. By proper choice of the transmission characteristics<sup>1</sup> of the amplifier stages across which the feedback took place, the following results were obtained.

TABLE 1

| Frequency | Relative Amplitude | Frequency | Relative Amplitude |
|-----------|--------------------|-----------|--------------------|
| 150 cps   | 0.2 %              | 275 cps   | 1.5 %              |
| 200 cps   | 0.4 %              | 300 cps   | 0.6 %              |
| 225 cps   | 1.0 %              | 400 cps   | 0.3 %              |
| 250 cps   | 100 %              | 1000 cps  | 0.1 %              |

With a selectivity as sharp as here indicated, it proved possible to make satisfactory measurements even with very large interfering inputs, if the rotational frequency was at least 400 c.p.s.

The first stage of the amplifier together with the input resistors and coupling condenser were contained in a small brass box fastened to the outside wall of the vacuum chamber where the

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<sup>1</sup>With the aim of avoiding phase shifts at those frequencies at which the amplifier tended to oscillate regeneratively.

lead from the vibrating electrode emerged. The input resistors and the condenser coupling them were coated with Amphenol 912-B coil dope and a grounded graphite guard ring encircled the condenser. With these precautions it was possible to attain stable amplifier operation on the most humid days. The tube, a 6J7G, was mounted antimicrophonically. From the first stage a long coupling lead led to the aluminum box containing the remaining stages. Observations of the amplifier output were made on the cathode-ray oscilloscope and on a rectifier microammeter shunted with a 2000 mmf. condenser to by-pass the slow variations due to noise fluctuations.

It may serve as an illustration of the techniques of the experiment to portray a typical run. After a thorough hand cleaning of the wall of the vacuum chamber to remove any dielectric films, the gallium pool was mounted inside and its surface was scraped clean. The rotor was mounted in the lathe, held by the 3/4" projection at the bottom, and centered by means of a dial indicator to within .0002". The alignment of the shaft was checked and corrected to within .0005" at its base. With a high speed tool which had previously been "cleaned" by cutting a scrap of duralumin, the entire accessible surface of the rotor was shaved to a fine finish. Without touching the surface of the rotor, it was transferred to a container to keep it free from dust. The electrode and its shaft were unsoldered from the piezo-crystal arm and fastened in a framework which could be mounted in the lathe. The electrode was then centered such that a shaving cut of .002" would generate a cylindrical surface of the same curvature as that of the rotor. With the same tool and similar precautions it was cleaned, and then resoldered to the crystal. By means of the ways carrying the crystal, the electrode was brought into close proximity to a dummy rotor which was mounted level in the vacuum chamber, and then by eye it was adjusted to levelness by rotating the crystal on its mounting. The electrical lead to the amplifier was soldered in place, and also the lead from the gallium pool to the potentiometer. The cooling water around the chamber was turned on, and the wax was melted with the ring burner. Then the rotor was placed on its support in the chamber, the cover was lowered into place, and the wax allowed to harden. If at any time during these operations the cleaned surfaces of either rotor or electrode were touched, the experiment



was considered spoiled and was started anew.

The main bearing and its oil connections and vibration-damping mounting were next assembled surrounding the shaft, and, in order, the supporting-air chamber, the bakelite ring, collet, driving rotor and nut were fastened in place and the rotating system was tested manually for free rotation on the supporting air. Again the wax was melted and, by careful adjustment of two variable clamps connecting the cover to the surrounding barricade, the alignment of rotor with respect to the electrode was set, observing the clearances through a long focus ten power microscope.

The free shaft between main rotor and main bearing was set at about one millimeter, and then the rotor was raised into contact with the Koroseal ring mounted on the bearing. With oil pressure in the bearing the vacuum pumps were turned on; it was infrequent that the wax seal to the cover proved leaky.

After more or less pumping time, depending on the particular experiment, the rotor was lowered to spinning position, the driving jets and upper bearing were locked in place and the oil lead to the bearing was connected. The supporting air was set at about 65 lbs. per square inch, and, with the oil pressure adjusted to 15 lbs. in the bearings, the driving pressure was turned full on to 80 lbs. The rotor rapidly accelerated through a low frequency vibration and thence continued up to a speed of from 500 to 800 R.P.S.; during this acceleration a continuous vibration of about 100 C.P.S. was felt in the cover of the chamber and in the upper bearing, although the edge of the main rotor appeared perfectly sharp under tenfold magnification. At some speed in this range the vibrations would cease suddenly, and thereafter no further troubles would be met. A trace of vibration at the rotational frequency was palpable in the upper bearing; above 1200 r.p.s. this was completely dampened by the bearing. At such speeds the noise is the only evidence of rotation. To reach a speed of 1000 r.p.s. takes about five minutes.

The progress of the rotation could easily be followed on the screen of the oscilloscope since an alternating current wave (the "rotational wave") of frequency equal to the rotational frequency was picked up by the stationary electrode.

After satisfactorily smooth rotation was obtained, the connection between the gallium pool and the potentiometer circuit

was made, but the galvanometer branch key in the potentiometer was left open. The gallium pool was slowly raised into contact with the rotor, as evidenced by an alteration of the pattern on the oscilloscope screen. Closing the potentiometer key completed the circuit. With the electrode set into vibration, it was moved towards the rotor by means of its slide mounting, observing its clearance through the windows provided. As this clearance decreased, the amplifier output increased, as was to be expected. On suitable adjustment of the amplifier gain and the potentiometer setting, the output was observed to pass through a minimum; the corresponding voltage reading was assumed to be the negative of the contact potential. Estimation of the position of this minimum proved to be most easily done by tuning the sweep circuit of the oscilloscope to the rotational frequency and minimizing the broadness of the wave trace.

Although theoretically the minimum is sharply defined as the intersection of two straight lines, in practice it proved to be rather broad. For this reason accurate estimation of its position (or, what amounts to the same thing for this experiment, of any reproduceable point on the response curve) was accomplished by an arithmetic interpolation between equal response values on each side of the minimum.

Values of the contact potential were thus obtained for various speeds and for various spinning periods. Since the contact potential was never constant at any one speed, nor when stationary, the drift rate of the potential as a function of the rotational speed was all that could be estimated.

In attempting to realize high D.C. sensitivity in these experiments, one must obtain, for a given A.C. amplification and a given tuning curve, a high conversion ratio of D.C. potential to A.C. signal. It was thought that larger amplitudes of vibration of the electrode would increase the conversion ratio from its usual value of about one-twentieth, and to this end several mechanical oscillators were tried. Ball bearing guides on the shaft of the electrode made little difference; a loudspeaker motor gave no improvement; a high speed air motor with eccentric drive rapidly burned out several sets of ball bearings. Next we tried a mechanical resonator in the form of a bent duralumin tuning fork, driven by the piezo-electric crystal through the bearing in the

chamber wall, and with the electrode mounted on one tine. With only moderate driving power we were thus able to obtain amplitudes of  $1/8"$ , as compared to a few thousandths of an inch before, and with extremely sharp resonance.

When measurements were tried with this resonator, the signal at the resonant frequency increased at least tenfold, but it was also observed that the minimum signal obtainable by setting the potentiometer was very much larger than usual, so that the overall sensitivity was actually greatly reduced. It was our usual experience that the signal obtained when the electrode was vibrated in the vacuum chamber with the rotor removed, and the minimum signal when making a measurement were about equal to the noise level of the amplifier. With the resonator both these signals were perhaps 25 to 50 times the noise level. Previous experience indicated that charges gathering on unshielded dielectrics in the neighborhood of the vibrating system could produce similar effects, and that these phenomena could be eliminated by adequate shielding of the insulators, especially the one on which the electrode was mounted. Only a slight improvement resulted from the best shielding geometrically permissible, even if the lead to the electrode were disconnected and suspended close by. This last eliminated the possibility that the extremely large oscillations of the connecting wire were responsible for spurious signals of the nature of stress potentials. It seemed likely that the phenomena were indications of the contact potentials existing between the electrode and the surrounding walls of the vacuum chamber, and that the relatively large capacity variations between them generated such large extraneous voltages; this guess was substantiated by the observation that lining the vacuum chamber with aluminum foil reduced the minimum signal, though not enough to warrant use of the resonator. However, this appears to be a promising technique for further study.

Two further sources of spurious and variable potentials proved easier to eliminate. Careful grounding of the main bearing greatly decreased the signal resulting from outside electromagnetic fields. Small bits of insulating oxide on the surface of the gallium pool made the contact uncertain and intermittent, but careful purification from contaminating aluminum prevented their rapid formation.



With the above precautions and a little luck, one could usually attain a D.C. sensitivity of ten to one hundred microvolts while the rotor was spinning, and perhaps to three microvolts while stationary. This, with an A.C. sensitivity of 0.1 microvolts (measured), corresponds to a conversion ratio of about 1/30. The ultimate limitation is the irreducible minimal noise signal plus certain sudden sharp variations in the minimal response which are more or less temporary in duration and which one can readily distinguish from noise fluctuations. It is possible that these are manifestations of cosmic rays or of the residual radioactivity of the surrounding materials.

One very unusual occurrence deserves mention. On one occasion, for a period of about one hour, the sensitivity of the measurements were of the order of 0.1 microvolt, on the stationary rotor. Though the drift rate of the potential made it impossible to reproduce measurements, yet for periods of many seconds one could obtain full scale deflections on the oscilloscope screen with one microvolt changes in the potentiometer settings. This sensitivity was never reattained, nor can it be easily explained. And yet, the most extensive checking during its occurrence failed to disclose anything extraordinary which could account for this anomalous sensitivity; it is one example of many of the complexity of the phenomena involved.

The results of even the few successful experiments obtained are complicated by some or all of the following observed factors. First, in a strict sense the values obtained cannot be said to represent the ideal definition of contact potential. It was observed that gross changes of perhaps as much as 0.2 volts in the position of the minimum occurred with changing of the clearance between the electrode and the rotor, sometimes amounting to actual changes in sense. Moreover, somewhat lesser variations in the value of the contact potential corresponded to changes in the amplitude of the vibration of the electrode. Thus it appears that some factor dependent upon the geometry of the apparatus is superimposed upon the geometrically independent contact potential. In the theory of the measurement it is assumed that the capacity between the vibrating electrode and grounded conductors shall be negligible compared to the rotor-electrode capacity; due to limitations of size it was impossible to attain this ideal condition, and this perhaps constitutes an explanation of the

above mentioned variations. Also, since the electrode has a very thin section parallel to the vibration axis, it almost certainly does not move as a rigid body. Flexure of the electrode at the vibrational frequency may result in stress potentials which would alter the equipotential character of the electrode surface periodically, and thus introduce an additional signal to the amplifier which would be a function of the amplitude of vibration. There is, however, no a priori reason to suppose that either of the aforementioned phenomena vary with rotational velocity, certainly not to the first order of magnitude.

Far more difficult to correct for are the variations of the contact potential with time. These changes varied at rates from a few tenths of a millivolt in ten minutes up to several millivolts. The rate was a function of the severity of the machining operation used in cleaning the rotor surface, the length of time elapsed after the machining operation, the pressure of the residual gases in the vacuum chamber and of the total pumping time, and in general asymptotically approached a limiting value under constant conditions, although only very slowly. Such changes may be interpreted in terms of the gradual changes in the surfaces with the release of internal strains, with formation of the oxide layer on the aluminum and the degassing of the surface, and are characteristic to all contact potential measurements. These changes may be accelerated by raising the surface temperature, and it is likely that some such attempts would be valuable. In lieu of such techniques it was necessary to use long pumping periods at high vacuum preceding the measurements, in order to attain a slower drift rate. By careful manipulation during the cleaning operation it was usually possible to attain a contact potential of less than 30 millivolts.

A few observations revealed a very interesting dependence of the contact potential on the recent electrical history of the apparatus. If one "followed" the drifting values of the contact potential with the potentiometer so as to keep the response always close to the minimal value, and then rapidly changed the potentiometer setting by say, one millivolt, the succeeding reading of the minimal position would be found to be displaced in the direction of the imposed voltage by perhaps 0.2 to 0.3 of a millivolt beyond what could be accounted for by an extrapolation of the previously observed drift rate. Such evidence of the elec-

trical variations within the system were persistent for periods up to many minutes, and for reproduceable observations one must very gradually approach the minimum setting, successively approximating it. In a circuit whose time constants are of the order of  $10^{-2}$  seconds it is not easy to account for these changes as evidence of variations within the conducting elements themselves. It is possible that dielectric absorption into the insulators between the gallium pool or the rotor and ground may be responsible. Furthermore, the well substantiated fact that the potential of an "isolated" body will not be constant raises the question as to whether the above mentioned drifting of the contact potential with time may not be partly due to a manifestation of the "partial isolation" of the spinning rotor contacting the gallium pool.

The most interesting indication of a correlation between the rotational velocity and potential variations were obtained in a six hour spinning the results of which are given in Figure 3.

In this particular experiment the electrode had been cleaned six days before; the rotor on the previous day. After two hours pumping at a pressure of  $5 \times 10^{-6}$  mm., the rotor was accelerated to 800 R.P.S. (A, Fig. 3). The form of the rotational wave observed is shown in Figure 4 A. The potential continued to drift, with subsequent alterations in the wave form as shown in Figures 4B,C,D,E, and F to correspond to points B,C,D,E, and F of Figure 3. During this period the sensitivity gradually decreased from ten microvolts to about one hundred microvolts, and both the rotational wave and the vibrational wave became erratic. At G, the speed was increased to 1670 R.P.S., without further alteration in the rotational wave form. At H, the rotor was slowed to 940 R.P.S. and at J the rotation was stopped. It was noticed that the vibrational amplitude of the electrode was very small, due to inadequate cooling of the piezo crystal; this accounted for the lowered sensitivity.

The marked break in the curve corresponds exactly to the change in angular velocity. The error of measurement of the experimental points is too small to appear on a scale of this size. The very interesting progressive simplification of the rotational wave forms is marked, with no further changes after an almost pure sine wave was obtained. Indeed, only rarely were the wave forms nearly as complex as Weissman usually observed.



Another indication of the same effect was obtained in the final experiment, the results of which are shown in Figure 5. Unfortunately the apparatus sprung a leak in the middle of the run, and further measurements were impossible. At point A, the speed was changed from 650 R.P.S. to 1400 R.P.S. The change in slope, though not as pronounced as in Figure 3, is evident.

## DISCUSSION

In view of the meager data collected on the behavior of the spinning system, no definite conclusions concerning the electrical properties of rotating metallic conductors are possible. In general, aims established by the work of S. I. Weissman are incompletely realized, though a more reliable and consistent technique has been developed for their study.

Among the most interesting of the phenomena observed is the slow rate of disappearance of the effects of sudden electrical disturbances in the system. The high sensitivity of the detecting apparatus to audio frequency variations in the rotor-electrode circuit is strongly indicative of a very short time-constant, and is thus in sharp contrast to these slow changes.

From the encouraging progressive simplification in the complexity of the "rotational wave" forms it would seem that an improvement in the technique of cleaning and handling the rotor has been effected. Since at no time in these experiments were any waves nearly as complex as those of Weissman's experience observed, it is possible that the elimination of all magnetic materials from the vicinity of the apparatus is responsible.

Though too few data have been gathered, I believe it highly likely that the observed change in the time rate of drift of the contact potential is a real phenomenon. The more rapid drift rate at higher speeds follows simply from the concept that the larger centrifugal stresses enhance the possibility of plastic flow of the rotor material with consequent relief of strains. If the higher drift rate establishes an equilibrium more rapidly, it suggests long spinning as a means for achieving constant potential. Moreover, if a dynamical E.M.F. of the order of 10-100 microvolts is to be detected, means will have to be developed for achieving more stable values of the contact potential than were usually observed. The rate of variation of the contact potential of even the stationary rotor was never less than several millivolts per hour, even after long pumping at high vacuum, and so only large deviations from the extrapolated potential values are discernible.

These experiences are not in complete agreement with the results of S. I. Weissman, who found that after long periods at high vacuum, the variations of the potential were generally less than here indicated. It ought to be noted, though, that the sensitivity of the measuring apparatus is adequate to the detection of changes in the range of microvolts, and perhaps even smaller.

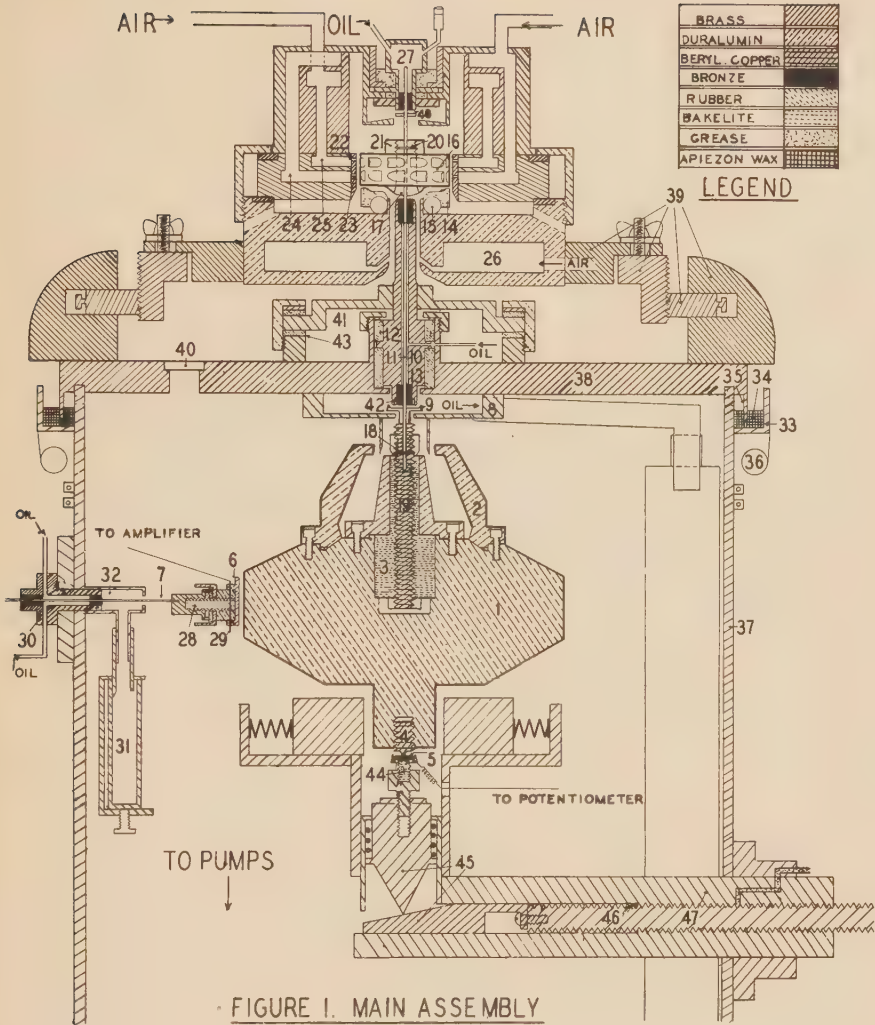
Two mechanical problems still present considerable difficulty. If a more stable dielectric material were available for the insulator between the rotor and its shaft, the frequent difficult rebuilding of the rotor suspension would be unnecessary. Of greater importance would be the development of more powerful means to vibrate the electrode, which would permit the use of a more rigid electrode. This would result in a better and more stable alignment of the rotor to the electrode, and also diminish the probability of spurious flexural potentials in the electrode itself.



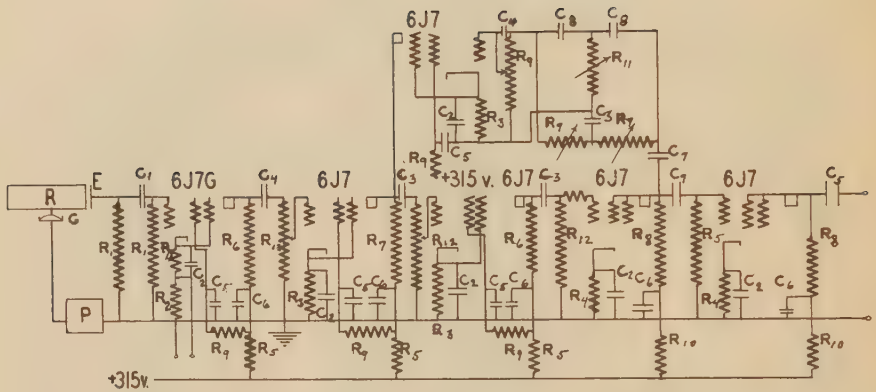


FIGURE 1. LIST OF PARTS

1. Body, main rotor
2. Oil receiving cup
3. Bakelite insulator
4. Contact point
5. Gallium pool
6. Electrode
7. Electrode shaft
8. Oil trap
9. Centrifuge oil disc
10. Main bearing
11. Rotor shaft
12. Rubber rings
13. Bronze bearing plug
14. Bakelite supporting bearing
15. Neoprene ring
16. Driving rotor
17. Collet chuck
18. Shaft lock pin
19. Main rotor chuck
20. Shaft lock pin
21. Collet closer nut
22. Upper driving jets
23. Lower driving jets
24. Driving air chamber
25. Driving air chamber
26. Supporting air chamber
27. Upper bearing
28. Electrode insulating screw
29. Electrode locking pin
30. Electrode bearing
31. Oil receiving cup
32. Oil retainer tube
33. Wax well
34. Apiezon wax
35. Cover sealing projection
36. Ring Bunsen burner
37. Vacuum chamber wall
38. Vacuum chamber cover
39. Support for driving mechanism
40. Glass window
41. Main bearing stabilizer
42. Koroseal ring
43. Rubber ring
44. Bakelite pool cup
45. Pool raising mechanism
46. Screw, pool mechanism
47. Nut, pool mechanism







|                 |               |          |
|-----------------|---------------|----------|
| R ROTOR         | R1 $10^8$     | C1 .0002 |
| E ELECTRODE     | R2 5          | C2 25    |
| G GALLIUM       | R3 1500       | C3 .004  |
| P POTENTIOMETER | R4 2500       | C4 .02   |
|                 | R5 50 000     | C5 1     |
|                 | R6 500 000    | C6 8     |
|                 | R7 250 000    | C7 .5    |
|                 | R8 20 000     | C8 .002  |
|                 | R9 300 000    |          |
|                 | R10 10 000    |          |
|                 | R11 125 000   |          |
|                 | R12 1 000 000 |          |

FIGURE 2. AMPLIFIER

CONTACT POTENTIAL  
IN MILLIVOLTS

80

64

48

32

16

0.

A

B

C

D

E

G

H

J

TIME IN MINUTES

0

32

64

96

128

160

192

224

256

288

FIG. 3

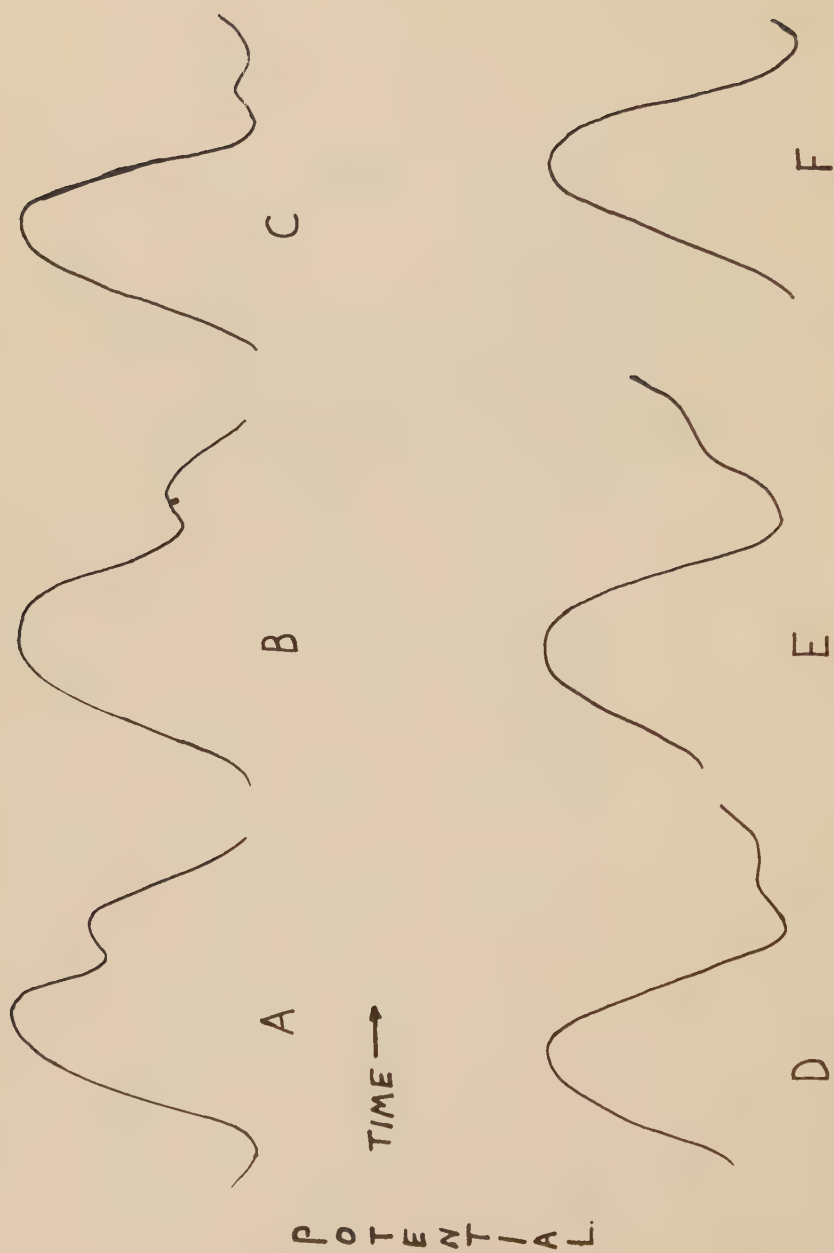


FIG. 4



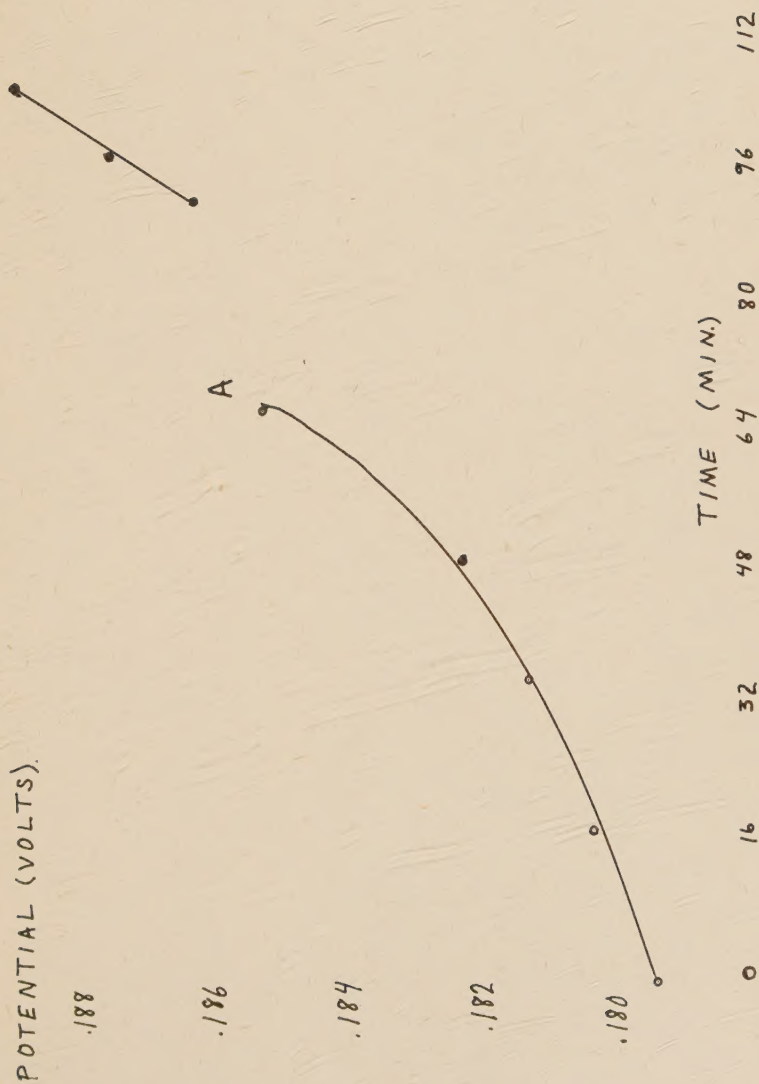


FIG. 5







